

## The Thorium Nuclear Power Cycle - Cleaner and Less Expensive

14<sup>th</sup> ICE and 42<sup>nd</sup> EGGES

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### ABSTRACT

Nuclear reactors currently provide about 18% of the world's electricity. Most are high-pressure, water-moderated reactors fundamentally similar to the system chosen by Adm. Rickover over fifty years ago. The primary fuel ("fissile") used in all of them is the relatively rare uranium isotope  $^{235}\text{U}$  (it represents only 0.7% of natural uranium), contained in solid state fuel assemblies along with typically 25x as much  $^{238}\text{U}$  "diluent". As the  $^{235}\text{U}$  is "burned", the in situ production (breeding) & partial burning of a second fissile material,  $^{239}\text{Pu}$ , from the otherwise inert  $^{238}\text{U}$  typically adds another 30% to the total energy output which raises overall raw uranium "burn" efficiency to about 1%. Since spent nuclear reactor fuel assemblies contain a good deal of residual  $^{239}\text{Pu}$ , two nations, France and UK, currently reprocess them to recycle it into new "Mixed Oxide" (MOX) fuel assemblies.

The fuel assemblies utilized by USA's civilian reactors contribute only 10% of the wholesale cost of electricity which means that there is little economic incentive for our utilities to use uranium more efficiently; i.e., burn more than ~1% of the total mined. However, there are several other factors that do dictate change. The first "change driver" is that today's approach is unsustainable because the World simply doesn't contain enough readily available  $^{235}\text{U}$  to supply Mankind's future energy needs if we choose to address climate change issues by substituting nuclear fission for carbonaceous fuels. Since the modest degree of recycling currently accomplished by France/UK costs more than it's worth, Mankind must either implement a more efficient  $^{238}\text{U} \rightarrow ^{239}\text{Pu}$  breeding/recycling system or switch to an entirely different nuclear fuel cycle. The second change driver relates to the current system's intrinsic waste issues: First, since today's reactors require enriched uranium, fueling them generates a "depleted uranium" waste stream approximately seven (4%/0.7%) times the size (mass) of that going into the reactors. Second, the same process which generates  $^{239}\text{Pu}$  also generates other long-lived (thousands to millions of years) transuranic (TRU) isotopes which render the disposition (or reprocessing) of spent fuel both problematic and expensive. The third change driver is the current system's "proliferation issues" - it requires the capability to isolate  $^{235}\text{U}$  and generates lots of  $^{239}\text{Pu}$  - the key ingredients of nuclear weapons.

For decades the USA's national laboratories devoted a great of resources to developing one alternative to today's once-through nuclear fuel cycle, the liquid metal (or sodium)-cooled, fast "breeder" reactor. The key difference is that the neutrons produced by fission are not significantly slowed via collisions with low atomic weight moderator atoms (e.g., the hydrogen in water) before they collide with other uranium atoms. Since "fast" neutrons react with actinide isotopes which don't fission in moderated reactors, fast reactors burn TRU-type

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waste more efficiently and *may* even produce (“breed”) significantly more plutonium from  $^{238}\text{U}$  than they consume.

Oak Ridge National Laboratory (ORNL) studied a fundamentally different approach to implementing civilian nuclear power from the early 1950’s until the Nixon administration downsized the program in 1973. ORNL’s molten salt breeder reactors (MSBRs) would generate their own fuel/fissile ( $^{233}\text{U}$ ) via neutron absorption by natural thorium ( $^{232}\text{Th}$  is roughly three times more abundant than is  $^{238}\text{U}$ ).  $^{233}\text{U}$  is a superior nuclear fuel because a lesser proportion of it transmutes rather than fissions than is the case with either  $^{235}\text{U}$  or  $^{239}\text{Pu}$ . This plus the fact that breeding starts at mass 232 instead of 238 means that a MSBR would generate orders of magnitude less TRU (esp.  $^{239}\text{Pu}$ ) per kilowatt-hr than today’s reactors. Next, since MSBRs only need  $^{235}\text{U}$  (or any other “outside” source of fissile material) during initial startup, a “nuclear renaissance” would not require new U enrichment plants. Furthermore, since both the  $^{233}\text{U}$  and  $^{232}\text{Th}$  would consist of fluoride salts dissolved in the low viscosity, molten salt solvent circulated between the reactor and its heat exchangers, these reactors would not require the fabrication, transport, storage, or reprocessing of discrete solid-state fuel assemblies. This plus the fact that they would be more thermally (and fuel) efficient than today’s reactors and less likely to either “blow up” or “melt down” means that they should be cheaper to build and operate.

The authors recommend that today’s solid-fueled, uranium-burning nuclear reactors eventually be replaced with thorium-fueled MSBRs. Nations that are just beginning to implement their own civilian nuclear power programs should consider going to them immediately. Nations that already possessing large numbers of reactors and having therefore built up large accumulations of spent fuel should also develop/implement molten salt reactors optimized for burning TRU recovered from the legacy waste.

## 1 INTRODUCTION

During our lifetimes (we’re both old enough to collect SS) we’ve seen society and technology become incredibly complex compared with the relative simplicity of earlier times. More to the point of this conference, during our time a burgeoning world population constantly squabbling over ever-dwindling natural resources – clean water, fossil fuels, food, etc. - and causing severe environmental degradation while doing

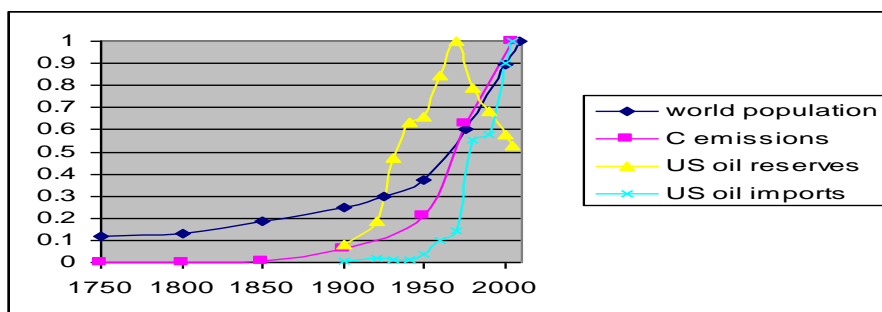


Figure 1: World population, World carbon dioxide emissions, US oil production, and US oil imports normalized to current values (EIA figures, WIKIPEDIA).

so has brought mankind to the point where it's somewhat questionable whether civilization will survive into the next century, let alone the more distant future. In other words, Mad Max's dystopian world might become reality by the time our grandchildren reach our age.

Figures 1-3 illustrate some of the problems that we are alluding to.

The world's total human population – now nearly 7 billion – is three times greater than it was when we were born and also, according to scientifically reliable authorities, about 3 times greater than could be supported without today's, highly energy-intensive, food production/distribution technologies. The world's total anthropomorphic carbon emissions (mostly CO<sub>2</sub> – a direct measure of total fossil fuel consumption) has burgeoned even more rapidly than has population, reflecting the fact that *some* folks standards-of-living have significantly improved (other's have deteriorated). Because the USA has been willing to accumulate huge balance of payment deficits & and serve as the Middle East's (military) police force, our thirst for oil has continued to rise (now over 20 million barrels/day) in spite of the fact that we reached the peak of the “Hubbert Curve” about 40 years before the world did. It is not just a coincidence that this country experienced its second-most serious post-WW II economic recession during the 1970's (just after we reached our “peak oil” point) and that the whole world, including the USA, is currently going through an even more severe recession now.

Figures 2 and 3 (WIKIPEDIA) illustrate that global warming is not only real but apt to cause the world that we grew up in to disappear if mankind doesn't *immediately* begin to change its “dirty” ways; i.e. virtually eliminate greenhouse gas (GHG) emissions by mid-century. “Business as usual” will push us over the “tipping point” by 2040.<sup>1</sup> Here in the USA, “change” must involve doing more than just switching to fluorescent light bulbs and paying another couple of generations of DOE contractors to produce more “studies” of a host of politically-correct alternative energy scenarios.

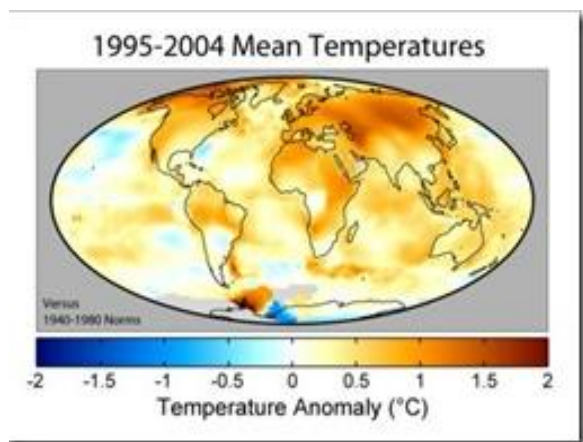


Figure 2 Temperature Anomalies 1995-2004

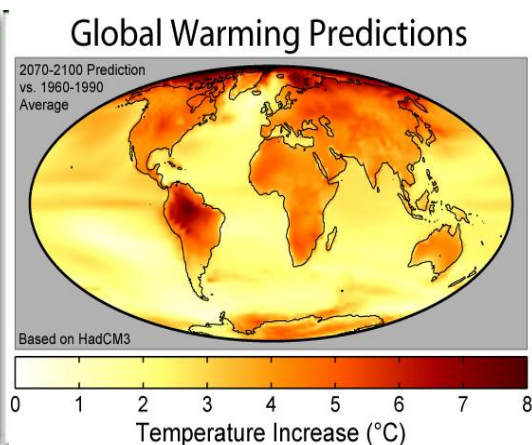


Figure 3 “Business as usual” temperature projection for the next century

## 2. TODAY'S RENEWABLE ENERGY ALTERNATIVES

Figure 4 (WIKIPEDIA) illustrates the main reason why we can't just switch over to the "renewable alternatives" – solar, wind, biomass, etc. – that are getting so much positive press these days – **all** "renewable" power sources are fundamentally unreliable.

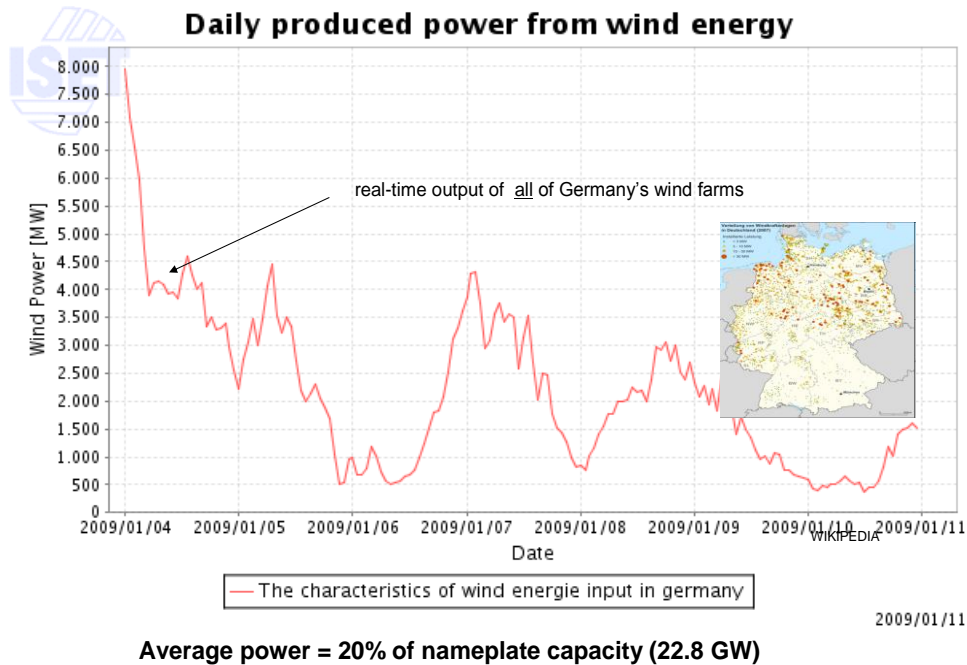


Fig. 4: Real time output of Germany's wind farms

Note that the total power production of all of the wind farms across a good-sized country varies tremendously and that the average power is far less than the system's nominal capacity. Solar power in most of the Earth's temperate regions (e.g., most of the USA and all of northern Europe and Asia) is even less reliable than is wind power. The other reason why wind/solar can't solve the problem we face is that both are extremely "land intensive"; i.e., both require covering vast amounts of land with huge, expensive collection systems. The fundamental reason for this is that the average amount of "free" power they provide per unit area of the earth's surface is very low – about 1.2 watts/m<sup>2</sup> for wind and 6-7 watts/m<sup>2</sup> for photovoltaic<sup>2</sup>.

In an increasingly hungry world "biofuels" constitutes a cruel hoax because it would take about 1200 square miles of farmland<sup>3</sup> to produce enough "biomass" (even if it happens to be that magic weed "switch grass"<sup>1</sup>) to fuel just one average-sized (one GW<sub>e</sub>) electric power plant. The industrialized world's heavily subsidized bioethanol/biodiesel programs have recently proven to be an embarrassment to some decision-makers because during

<sup>1</sup> According to switch grass enthusiasts, it'll thrive in any kind of soil without receiving any of the inputs - fertilizer, irrigation water, herbicides/pesticides, etc. – required by normal crops.

the last three years, those programs helped to double global food prices – the first global impact of [peak oil](#). In 2007 alone, the price of corn went up by 30%, rice by 74%, soy beans by 87%, and wheat by 130%. The people hit hardest by such increases are, of course, the poor. The grain needed to fill a SUV's tank with bio-ethanol would feed a person for one year. The fact that growing food for cars has taken precedent over growing food for people demonstrates just how hooked on petroleum we've all allowed ourselves to become.<sup>3</sup>

Consequently, algae-based biomass alternatives have recently become especially attractive (politically correct) to politicians, fossil energy suppliers, and the folks who derive their incomes from either performing or managing renewable energy R&D. Their rationale include: 1) even poor people don't eat algae; 2) some varieties of algae contain over 50% "oil" (dry-weight basis) and *could* therefore, in principle, be converted to biodiesel; and 3) it is quite simple to demonstrate that with the help of cleverly designed bioreactors, algae can "eat" the carbon dioxide in the off gas streams emitted

BASIS document: *"Airlift Bioreactors for Algal Growth on Flue Gas..."*,

Ind. Eng. Chem. Rev., Vol 44, No 16, 1654-1663, 2005. (MIT)

Raw Data: in bright sunlight, the recirculating algae slurry absorbed/utilized ~ 80% of the CO<sub>2</sub> in the flue gas feed stream

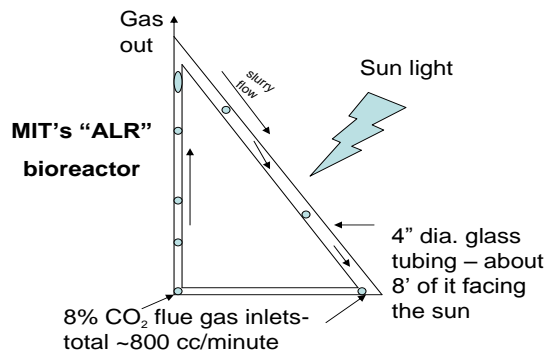


Figure 5. MIT's "Air Lift Bioreactor" (ALR)

by fixed fossil fuel combustion systems; i.e., this sort of scheme could constitute a way to render those polluters "GHG-neutral". To demonstrate how unrealistic such schemes are, let's take a closer look at one of the peer-reviewed research reports which has generated a great deal of favorable internet buzz among "greenies" recently (Figure 5). Under optimal operating conditions MIT's state-of-the-art bioreactor absorbed most (~80%) of the carbon dioxide in the flue gas providing both the algae's carbon (food) source and the system's energy requirements (recirculate the slurry and keep the inner surface of the glass clean). Since the flue gas contained 8% by volume CO<sub>2</sub> (typical) and its flow rate was 800 cm<sup>3</sup>/minute, a simple calculation reveals that MIT's gadget can indeed convert ~1.7 milligrams of GHG/sec into a potential biodiesel "precursor" (sloppy green slime). However, since a typical-sized (one GW<sub>e</sub>) coal-fired power plant flue gas

emitter generates about 250 kilograms of CO<sub>2</sub> per second, an even simpler calculation reveals that under optimum conditions, it would take about 150 million ALRs to absorb the GHG emitted by one power plant. Of course, this system wouldn't work nearly as efficiently whenever the sky happened to be cloudy or at all during the night. Furthermore, the ALRs needed to accomplish this for just one coal fired power plant would cover roughly 14 square miles and require about 1.9 million tons of glass to fabricate.

Is this *really* the sort of scheme to which our tax dollar-supported alternative energy experts should be devoting their attention?

In most of the civilized world, hydropower is already almost fully maxed-out and, while it is considerably more reliable than wind or solar, nevertheless still depends upon how much rain happens to fall in a particular drainage. Furthermore, over the long haul, hydropower is "unsustainable" in that all reservoirs eventually fill with mud and global warming is apt to further reduce total rainfall/snow pack in many regions.

The bottom line is that modern industrialized civilization requires reliable power which, in turn, means that today's over-hyped "renewable alternatives" can never constitute more than about 20% of our total energy supply.

How much energy are our descendants going to need? To arrive at a ball-park number, let's first see how much energy we use<sup>2</sup>. Recent EIA figures indicate that the USA's ~330 million people consume roughly 97 quads (quadrillion BTU) worth of raw energy per year (mostly fossil fuel) to generate about 42.5 quads worth of useful energy. The difference between 97 and 42.5, or 54.5 quads, is wasted primarily due to the physical limitations inherent to the Carnot cycle; i.e., the USA burns an inordinate fraction of its fuel in its *ad hoc* transportation "system's" internal combustion engines (mostly automobiles & trucks). Electricity constitutes 13.5 of the 42.5 useful quads we're using, to which 104 nuclear reactors (about 1 GW<sub>e</sub> each) contribute about 2.7 quads – three times as much as all other "green" (GHG-free) sources (wind, solar, hydro, & geothermal) put together.

A totally clean & green future would require us to substitute GHG-free electricity for virtually all fossil fuels. This would mean adopting the same sort of fully-electrified fast rail/tram public transportation system that France and Japan have already implemented, using compact battery powered cars for short personal commutes, building sufficient new railway infrastructure to move goods where only trucks can go now, electrifying most industrial processes (e.g., substitute electrolytic hydrogen for the methane-derived hydrogen currently used in ammonia production), and making whatever internal combustion engine fuel needed for special applications (e.g., the military's jets & logger's chain saws) from electrolytic hydrogen plus nitrogen and/or renewable carbon (this might constitute a *reasonable* scenario for biomass utilization). Our grandkids would also be able to do some "new" things that would improve their quality of life –

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<sup>2</sup> Total US energy use per capita has been essentially flat for over two decades because Mr. Reagan & his successors thought that it would be a great idea - at least for the folks that matter in the political arena - to "outsource" much of our nation's industrial capacity & switch over to a "service economy" instead. Since outsourcing killed much of our heavy industry, the USA is no longer capable of building more of the sorts of reactors comprising our current civilian nuclear reactor fleet without outside "help".

things like desalinating seawater (a single 1 GW<sub>e</sub> nuclear reactor's waste heat could desalinate enough water to irrigate about 120 miles<sup>2</sup> of desert or provide the domestic needs of a half-million city-dwellers) and return rivers presently choked with hydroelectric dams (like the lower Snake) to their original free-flowing state.

Since “embracing” this much change would force our political leadership to adopt policies which would reindustrialize our county, I suspect that our grandchildren will require even more useful energy per capita than we do – probably twice as much or about 8.6 kilowatts/person.

### 3 THE NUCLEAR ENERGY ALTERNATIVE

How could we produce that much clean reliable power? Thirty five years ago, ORNL's ex-Director, Alvin Weinberg and a colleague, H. E Goeller, wrote a seminal essay (“The Age of Substitutability” – see OSTI 5045860) to refute the “Club of Rome's” dire predictions about humanity's fate when the oil runs out (see “*Limits to Growth*” and “*Mankind at the Turning Point*”). They pointed out that nuclear fission (not nuclear fusion, which in their opinions was apt to remain a will o' the wisp) *could* constitute a viable “technological fix” for the otherwise inevitable Malthusian Catastrophe *if* we were to apply the same sort of dedication to practical problem-solving evinced by General Groves during the Manhattan project and subsequently by Admiral Rickover as he was “nuclearizing” the US Navy<sup>3</sup>. In particular, they observed that success would require our county to eschew its normal business-as-usual/muddling-through approach to addressing complex technical issues, especially ones for which “embracing change” is apt to generate vigorous push-back by industrial lobbyists and the folks who employ them.

Table 1 excerpted from Weinberg and Goeller's paper illustrates the gist of their thesis: the stuff, “CH<sub>x</sub>” (coal, petroleum, kerogen, and methane - mostly burned to carbon dioxide to produce energy, that modern civilization uses more of than anything else, including such bulky things as steel, aluminum, cement, and even gravel/rock, is both rare (about 4 parts per million) and rapidly being used up. However, it also shows that if mankind chooses to implement a genuinely sustainable *and* inexpensive alternative energy source (or sources), the same earth's crust contains plenty of everything else that we're apt to need for millennia.<sup>4</sup>

Their proposed “technological fix” invoked a worldwide nuclear renaissance implemented with thousands of large breeder reactors. Breeders would be necessary because the sorts of once-through power reactors currently used are fueled with <sup>235</sup>U<sup>5</sup>.

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<sup>3</sup> This paper also rather presciently observed that anthropomorphic CO<sub>2</sub> would likely cause the sorts of “climate change” problems which are now obvious to everyone but the feeble minded and folks who choose to be oblivious.

<sup>4</sup> Cheap energy would mean that mankind would no longer have to rely upon naturally-concentrated ores for its other material needs; e.g., aluminum could readily be extracted from common clay instead of from the relatively rare mineral bauxite.

<sup>5</sup> In practice, roughly 30% of the total energy generated in conventional reactors is derived from <sup>239</sup>Pu “bred” in situ from the much larger amount (typ. 30x) of non-fissile <sup>238</sup>U which accompanies <sup>235</sup>U in typical reactor fuel assemblies. That figure (30%) is barely enough to compensate for the fact that a good deal of the <sup>235</sup>U originally present in raw uranium ore is lost during subsequent fuel fabrication operations, e.g., “enrichment”.



Since that isotope comprises only about 0.2% of the world's potential nuclear fuel supply and is both difficult and politically problematic to isolate, it is too expensive to represent a truly "sustainable" fuel<sup>6</sup> for everyone (fine for a few submarines though) .

"Demandite"-the stuff that an industrialized society requires (mole%)

CHx=0.802 (almost entirely burned to produce energy); SiO<sub>2</sub>=0.112;  
 CaCO<sub>3</sub>=0.0045; Fe=0.011; N=0.0076; Cl=0.0063; O=0.0053; Na=0.0053;  
 S=0.0023; Al=0.0011; P=0.0008; K=0.0008, Mg=0.0004;  
 (Cu+Zn+Pb)=0.0004; (Mn+Ba+Cr+F+Ti+Ni+Ar+Sn +..)=0.0008

### Composition of the Earth's Crust

O=0.588; Si=0.193; H (oxidized)=0.066; Al=0.051; C (oxidized)=0.015;  
 Ca=0.018; Na=0.014; Fe=0.013; Mg/K=0.012; Ti=0.0016; Cl=0.0014;  
 S=0.0009; F=0.0007; P=0.0004; CHx(accessible)=4x10<sup>-6</sup>; Th=1.7x10<sup>-7</sup>;  
 U=5.8x10<sup>-8</sup>; 235U=4.1x10<sup>-10</sup>

Table 1. The mismatch between our current needs and availability

## 4. THE MOLTEN SALT BREEDER REACTOR ALTERNATIVE

This brings us to the real subject of this paper - why one particular "old idea", molten salt breeder reactors (MSBRs), represents the best "alternative energy" option. First of all, let's list the drawbacks of both today's "light water reactors" (LWRs) and the somewhat "safer" Gen III (or Gen III<sup>+</sup>) versions currently on the drawing boards

Issues common to all LWRs include:

- They are intrinsically expensive because their extreme operating pressures (from ~1000 psi for today's least efficient LWR to ~3000 psi for some of the proposed Gen 3/Gen3+ models) require massive containment vessels for safety.<sup>7</sup>
- They are expensive to fuel due to a combination of poor thermal-to-electrical efficiency (another Carnot cycle limitation - they operate at only ~ 300°C), limited fuel assembly lifetimes, and expensive fissile material (enriched uranium)
- LWRs are also rather "dirty" because all spent enriched uranium-based fuel assemblies contain enough plutonium along with lesser amounts of "minor actinides" (MA) to render waste management extremely problematic but not enough to make "recycling" (reprocessing) economically viable.

<sup>6</sup> The world currently would need about 10,000 GWe's worth of nuclear generating capacity (about 10,000 reactors) to become totally "green". Since today's reactors consume about 200 tonnes of raw uranium/GWe/year, the nuclear industry's best guess of the world's "affordable" uranium reserves (i.e., 1.6x10<sup>7</sup> tons, [http://www.ne.doe.gov/neac/Meetings/June92009/ANTT\\_Final\\_report\\_209\\_meeting.pdf](http://www.ne.doe.gov/neac/Meetings/June92009/ANTT_Final_report_209_meeting.pdf)) corresponds to an 8 year fuel supply.

<sup>7</sup> At present, the world possesses only one forging facility capable of making a full-sized (~600 ton) LWR reactor vessel, Japan's JSW. JSW presently has a three year back log.



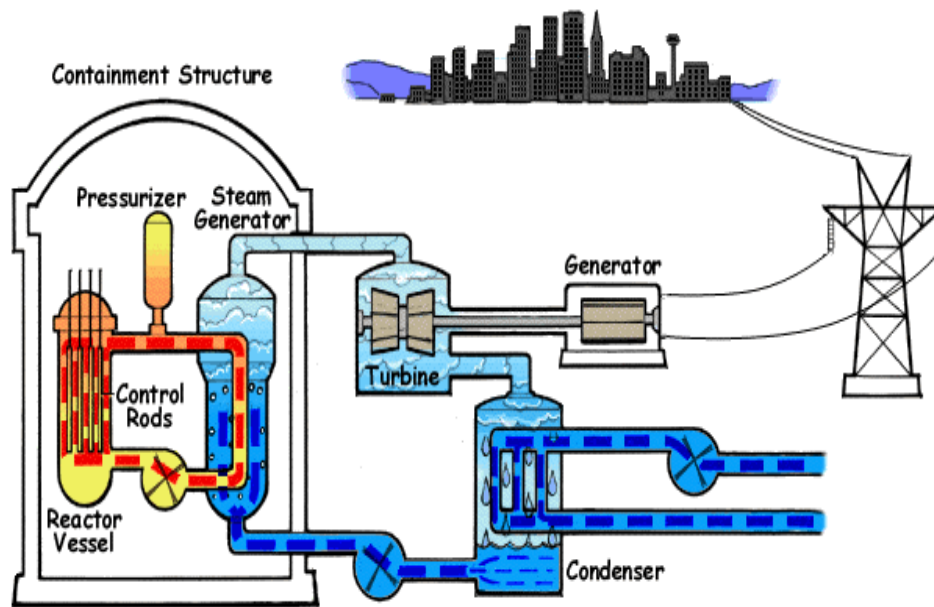


Figure 6: Light water reactor schematic

- LWRs are “unsustainable” because they burn only  $^{235}\text{U}$  (not “uranium”) and don’t breed nearly enough plutonium to refuel themselves regardless of how often their fuel is “recycled”. If the USA’s population remains constant, our descendants’ ~8.6 KW/person energy requirement corresponds to about 2830 1 GW<sub>e</sub> reactors - enough to consume all of the world’s “affordable” uranium within 30 years.

The huge head start due to Admiral Rickover’s dogged determination to build practical LWRs for his submarines plus the fact that the USA was able to produce large quantities of enriched uranium before its trading partners could, constitute the main reasons why most of today’s civilian reactors are LWRs<sup>5</sup>. By the time that other countries were able to catch up, US manufacturers had already captured most of the world’s civilian nuclear reactor market - often by deliberately low-balling construction bids, knowing that they could make up for any immediate losses with subsequent fuel service contracts.

Both the LWR’s inventor, Alvin Weinberg, and his student, Admiral Rickover, subsequently expressed some reservations about the way the USA had gone about implementing civilian nuclear power. Rickover thought that nuclear power was simply too dangerous to turn over to the sorts of “undisciplined” personnel he’d met during his visits to America’s electrical utilities. Weinberg’s main reservation<sup>8</sup> was that the LWR fuel cycle is too unsustainable to provide the vast amounts of power that the USA would eventually need. Consequently, during his 23 year tenure as ORNL’s Director, he managed to keep a series of low-budget “Homogeneous (liquid fueled) Reactor” projects

<sup>8</sup> Dr. Weinberg’s frankness about his reservations (in a report written in 1972, he’d used the phrase “Faustian Bargain” to characterize nuclear power) is why the AEC abruptly downsized him in 1973.

limping along<sup>9</sup> because he thought that this approach might eventually prove to be the best way to facilitate his vision of a clean, prosperous, nuclear-powered world when the cheap oil finally ran out.

#### 4.1 The Hows and Whys of MSBRs

Why did Weinberg feel that way? The best way to explain this is to show how a simple MSBR would work (Fig. 7). This example<sup>10</sup> consists of a spherical “core” tank roughly four feet in diameter within a larger tank, both of which contain low-melting solvent salts constantly recirculated between their respective vessels and heat exchangers. The innermost or fuel side tank’s solvent salt - a eutectic of  ${}^7\text{LiF}$ <sup>11</sup> and  $\text{BeF}_2$  (FLiBe – pronounced the way it looks) contains a small amount (less than one mole percent) of fissile material -  ${}^{233}\text{U}$  in the form of the salt  ${}^{233}\text{UF}_4$ . The outer “blanket” tank would contain ~25 mole percent of “fertile”  ${}^{232}\text{Th}$  in the form of  $\text{ThF}_4$  dissolved in  ${}^7\text{LiF}$ . The core tank’s wall or “barrier” material would be made of a material transparent to neutrons (e.g., a carbon-carbon composite material similar to a Space Shuttle ‘tile’) to

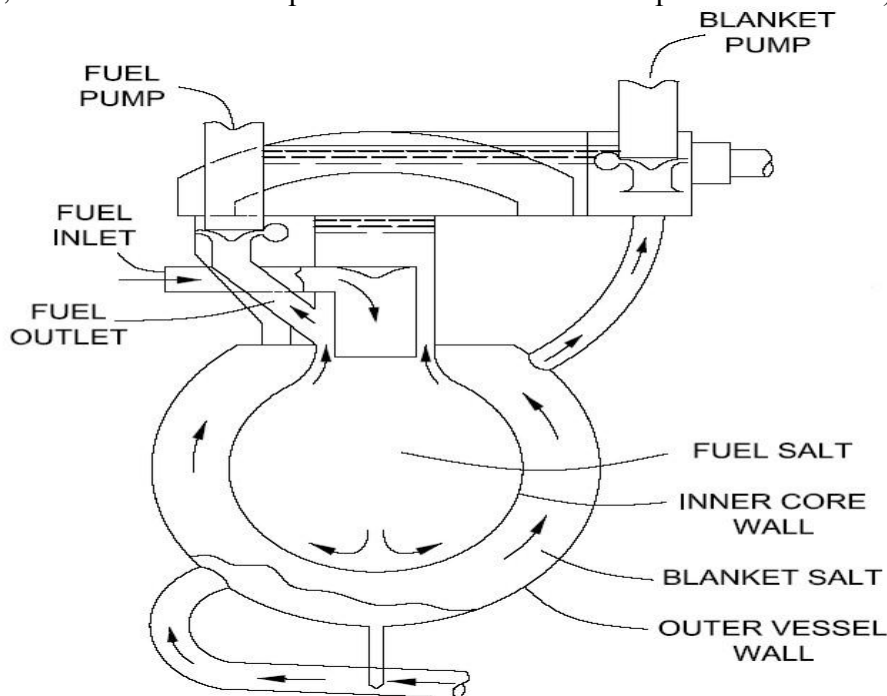


Figure 5: ORNL’s spherical tank-within-a tank, two salt<sup>12</sup>, molten salt breeder reactor

<sup>9</sup> The AEC and the US military were perfectly content with the breeding performance of Argonne National Laboratory’s (ANL’s) plutonium-generating LMFBR and were therefore unwilling to spend much money on Weinberg’s brain child.

<sup>10</sup> This is doc. ORNL 2751’s “case 36” differing only in that its core tank is made of something that doesn’t absorb neutrons (e.g., a CC or CCSi composite) instead of Hastelloy N and that the surrounding blanket salt layer is three feet instead of two feet thick. These changes would raise this reactor’s “clean core” Breeding Ratio (BR = fissile generated/fissile consumed) from ~0.89 to ~1.05.

<sup>11</sup> FLiBe is made with  ${}^7\text{Li}$ , not “natural” lithium because  ${}^6\text{Li}$  strongly absorbs neutrons.

<sup>12</sup> As opposed to the “one salt” types usually depicted in documents purporting to describe MSBRs. The physical difference between them is that the thorium is added to the fuel salt – not in a blanket salt.

permit at least one of the ~2.3 neutrons generated by fission of an atom of  $^{233}\text{U}$  in the core-salt “leaks” out into the blanket tank where it would be absorbed by an atom of  $^{232}\text{Th}$ , transmuting it to  $^{233}\text{Pa}$  which would then decay to another atom of  $^{233}\text{U}$ . Not depicted in figure 7 is the tiny<sup>13</sup> salt “clean-up” plant that would continuously; a) transfer “new” fissile generated in the blanket salt to the fuel salt; and b), remove fission products from the latter.

Here’s why this sort of reactor is “best”.

- The characteristic rendering it genuinely “sustainable” is that it produces its own fissile from a material ( $^{232}\text{Th}$ ) which is roughly 500 times more abundant than  $^{235}\text{U}$  and doesn’t have to be “enriched” in order to work. Today’s hullabaloo about Iran’s decision to also get into the nuclear reactor business suggests that conventionally-implemented nuclear power’s requirement for large-scale enrichment facilities constitutes one of its most controversial (and also most expensive) issues.
- It runs steady-state rather than discontinuously as do most solid-fueled reactors, which translates to less down time. The first reason for this is that its fuel consists of an ionic liquid which is both absolutely immune to radiation damage and readily purified on a continuous basis – which translates to no fission product (FP) “poison” build up. The second is that fresh fissile ( $^{233}\text{U}$ ) is added to the core at the same rate as it’s consumed.
- The reactor’s core would operate at near atmospheric pressure (certainly under 50 psi) rather than several thousand psi. The reason for this is that it operates at a temperature ~500 Centigrade degrees lower than the boiling point of either of the liquids (molten salts) within it - not ~200 Centigrade degrees higher as is the case with LWRs. This means that the driving force for a “core disruptive event” (explosion) is ~3 orders of magnitude less than it is in a LWR/, which, in turn, means that safe operation wouldn’t require a 600-ton reactor vessel – something that’s about as physically strong as a conventional hot water heater tank would probably be OK. It also suggests that MSBRs should be cheaper to build.
- This particular MSBR<sup>14</sup> would require a much smaller fissile inventory than any other equally powerful reactor. The first reason for this is that fission takes place in a “clean” core (one not containing stuff that absorb neutrons; e.g., burnable poisons, water, zirconium, stainless steel, large amounts of fission products, etc. ) and which therefore doesn’t have to contain extra fissile to overcome their “poisoning” effects. The second reason, germane to comparisons with any sort of LMFBFR (aka SFR or IFR), is that its fuel recycling (clean-up) system contains only a tiny fraction of the total fuel cycle’s fissile inventory– not a LMFBFR’s

<sup>13</sup> “Tiny “ because the molten salt slipstreams processed by the cleanup system would be small - a few liters per hour – and the operations it performs (e.g. vacuum distillation and gas sparging) don’t require large equipment

<sup>14</sup> There are many ways to build a MSBR - some don’t make much sense.

approximately five times as much dictated by the fact that it utilizes solid fuel assemblies. A third reason, again relevant to comparison with LMFBRs, is that it utilizes epithermal (relatively slow moving) neutrons rather than FAST neutrons – since fission cross sections are higher for slower moving neutrons, less fissile is required.

- Another handy feature was revealed during the approximately three years that ORNL operated its 10 MW pilot-scale reactor, the “Molten Salt Reactor Experiment” (MSRE)<sup>6</sup> i.e., it naturally tends to “follow the load” meaning that as less/more energy is extracted by its heat exchangers (load changes), less/more heat is produced. The reason for this is thermal expansion - as the fuel salt gets warmer, the fixed-size core “tank” contains less fissile which throttles-down the nuclear “fire.” This has two consequences; 1) because a MSBR could operate efficiently over a wide range of load demands, it would not just be useful for providing “base load” power, and, 2) it can’t “melt down” because high temperatures automatically reduce power<sup>15</sup>.
- MSBRs would operate at ~700°C, much higher than a LWR and a couple hundred degrees hotter than a LMFBR. This means both that is a much better “process heat” provider<sup>16</sup> and that the turbines powered by its heat exchangers could generate approximately 50% more electricity per pound of fuel (fissile) consumed than a LWR’s (another manifestation of Mr. Carnot’s law) .
- A final advantage/characteristic is that MSBRs would generate waste that is both easier and cheaper to manage than either that of either today’s reactors or DOE/INLs current Gen IV front-runners (VHTR or SFR) because it doesn’t

Actinide waste	LWR* kg/GWe·yr	MSBR* kg/GWe·yr
U (all isotopes)	26,000	<1
Pu (all isotopes)	440	0.024
Np (all isotopes)	31	0.017
Am	27	0.0017
Ce	4.4	0.009
FP	1271	866
<p><b>* figs. from “Review of Molten Salt Reactor Technology”, MOST Final Report, EUROPEAN COMMISSION, 5th EURATOM FRAMEWORK PROGRAMME, October 2005, and Ref 5, fig 1.11. Assumes 30% thermal-to-electric efficiency for PWR, 44% for the MSBR.</b></p>		

<sup>15</sup> This “safety characteristic” would be backed up by freeze plugs which would melt if the reactor somehow managed to overheat, dumping its fuel salt into a critically safe tank(s).

<sup>16</sup> For example, since the Haber-Bosch ammonia process operates at about 500°C, a ~300°C LWR couldn’t directly supply its process heat - a MSBR could.

generate the huge amounts of long-lived TRU that currently render spent fuel disposal so controversial (and expensive) – only the much easier to manage short-lived FP salt-waste isolated by its salt clean-up system<sup>17</sup>. The reason for this is that fissile “breeding” starts at mass 232 – many steps below plutonium’s mass 239 – rather than immediately next to it at mass 238. An additional waste-related benefit is that a MSBR would generate less total waste because: a) its greater thermal efficiency means that it would generate about one third less FP/watt·hr ; and b) its waste FP would not be accompanied with the <sup>238</sup>U and fuel cladding materials comprising the bulk of a spent LWR fuel assembly.

Since a four-foot diameter spherical reactor is too small to safely generate more than about 100 megawatts of electricity, more powerful MSBRs would have to be configured differently. Why? The key factor to keep in mind is that in order to achieve “breakeven”, at least one neutron per fission must leak from the core to the blanket<sup>18</sup>. However, because FLiBe’s neutron absorption cross section is not zero, even an absolutely “clean” (no FP) F<sup>7</sup>LiBe-filled spherical core can’t achieve breakeven if it’s much bigger than four feet across. The solution to this was pointed out by David LeBlanc two years ago (<http://thoriumenergy.blogspot.com/2007/08/modified-geometry-2-fluid-molten-salt.html>). – switch to a cylindrical (Fig 8) rather than a spherical core tank. The key to designing a “tube-in-shell” configured MSBR is “buckling” – the

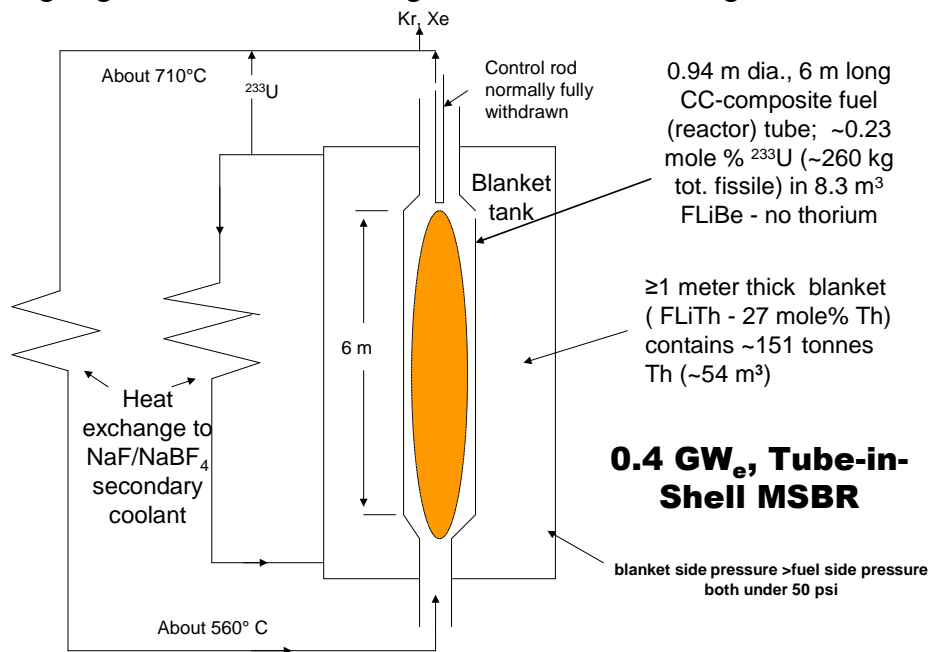


Figure 8: 400 MW<sub>e</sub> tube-in-shell MSBR

<sup>17</sup> This salt-waste would contain the precious medical radioisotopes (e.g., <sup>99</sup>Mo) now in such short supply in a form that facilitates separation. The genuine waste could be sealed up in stainless steel cans, allowed to cool off for a few years, and then shipped off to WIPP – an already implemented and genuinely competent radwaste repository (no more interminable Yucca Mountain “studies”).

<sup>18</sup> “Breakeven” means that the reactor produces exactly as much fissile as it uses; i.e. BR=1.

relative degree of neutron leakage exhibited by different-shaped cores. Since the cylindrical-to-spherical buckling factor is about 0.77, a 3.06 ft (0.94 meter) diameter cylindrical core of any length (volume) would possess about the same breeding characteristics as a 4 ft diameter spherical core. This means that MSBRs capable of generating virtually any amount of power could be produced by simply varying the total length of 0.94 meter diameter cylindrical core tubing immersed in the blanket salt tank. Other parameters include the velocity of the fuel salt within the core, its end-to-end temperature differential, and the core's power density (watts/cc). For example, if we need a break even-capable 400 MW<sub>e</sub> MSBR<sup>19</sup> and set those parameters at 2 meters/s, 200 watts/cc, and 150 Centigrade degrees, it would be about 6 meters long (figure 8).

How much fissile would this reactor require? ORNL reported (case 36 ORNL 2751) that a "clean core" (no FP), four foot diameter, carbon-walled spherical MSBR would achieve criticality with ~0.16 mole% <sup>233</sup>UF<sub>4</sub> and initially exhibit a BR of ~1.05. Consequently, if we assume an additional core volume's (4.16 m<sup>3</sup>) worth of fuel salt in this reactor's external piping/HXs etc., and that its salt clean-up system operated at a rate that just achieves break-even raises its steady state <sup>233</sup>UF<sub>4</sub> requirement to 0.23 mole% (not unreasonable), its total fissile inventory would be about 263 kg - roughly an order of magnitude lower than that of an equally-powerful LWR.

Here's why MSBR energy would be genuinely sustainable. Let's assume that the first kilometer of the earth's crust is "accessible" (we're already drilling much deeper for oil). If we then assume an average density of 2.7 g/cc, the mass of the earth's accessible crustal land mass works out to about 4.2E17 tonnes. According to recent EIA figures, the world's total fossil fuel (CH<sub>x</sub>) reserves (coal + shale kerogen + petroleum + natural gas) is 843+500+170+125, or 1513 gigatonnes. This means that the weight fraction CH<sub>x</sub> in the accessible crust is about 1513E9/4.2E17, or 3.9 ppm. USGS figures indicate that average crustal rock contains about 12 ppm Th by weight, which adds up to a total of 4655 gigatonnes. At 200 Mev/atom, the fission of one gram of thorium via MSBR would produce about 8.3E10 Joules of energy and no GHG. The combustion of one gram of an average CH<sub>x</sub> produces about 37,000 Joules of energy and about 3.1 g of GHG. Consequently the relative amounts of energy potentially available to us from thorium to that in all of mankind's remaining fossil fuel (maybe a hundred year's worth) is:

$$(4655/1513)(8.3E10/3.7E4) \text{ or } 6,800,000:1$$

### 4.3 Salt Clean Up

Keeping a two-salt MSBR at steady state would involve three clean up technologies:

- Inert gas sparging (fuel salt only)
- Fluorine volatility based separations (both salt streams)
- Bulk FP removal via distillation (fuel stream only)

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<sup>19</sup> If we needed 1200 GW<sub>e</sub> instead, one way to do it would be to put three such core tubes into a single large blanket tank.

Inert gas sparging would involve continuously bleeding helium into the inlet of the fuel salt's pump bowl to flush out (sparge) inert gas FP (the most important of which is  $^{135}\text{Xe}$ ), most of the radioiodine, and a substantial fraction of several noble metal FP in the form of an elemental "smoke". After the FP contaminants are filtered/absorbed from the helium, it would be recycled.

"Fluoride volatility" (ONRL 4574) serves three purposes: 1) transfer fresh  $^{233}\text{U}$  from the blanket to the fuel salt; 2) isolate  $^{233}\text{U}$  from a fuel salt slip stream before FP are removed from it (next paragraph); 3) remove Np and several FP (Tc, Ru, Mo, I, Nb, Rh, Te, Sb) that also form volatile fluorides from that slip stream. It involves counter current contact of molten salt with fluorine gas to convert  $^{233}\text{UF}_4$  to gaseous  $^{233}\text{UF}_6$  which is sparged out with helium & sorbed onto chilled NaF pellets - Np and the aforementioned FP covolatilize along with the uranium. After it's been cleaned-up via selective volatilization from the salt pellets, the  $^{233}\text{U}$  would be transferred back to the fuel salt stream via reduction with gaseous  $\text{H}_2$  with a bubbler.

After uranium is removed from it, the aforementioned slipstream would be introduced into a simple "one plate" vacuum distillation unit (ONRL 4577) to boil off the FLiBe. The involatile FP (the most important of which are the rare earth elements, e.g.  $^{149}\text{Sm}$ ) in the still bottoms would be pumped over to a waste tank and the purified FLiBe recycled.

The total amount of FP waste generated/recovered per year would be about 870 kg/GW<sub>e</sub>. Total radwaste generated per year would be 5-10 times that figure and consist primarily of used clean up reagents/sorbents plus FLiBe. The core tube, approximately two tonnes - mostly graphite - would also have to be discarded/replaced occasionally<sup>20</sup>.

The rates at which salt clean up would be performed is characterized by "cycle time" - total salt volume/process flow rate. Typical clean up cycle times would be on the order of once/2 weeks for the blanket salt<sup>21</sup> and once /2 months for the fuel<sup>22</sup>.

A fourth cleanup technology mentioned (or tacitly assumed) in most descriptions of MSBRs (or MSR) is "Liquid Bismuth Reduction/Extraction" (LBR/E). It invokes multistage counter-current liquid-liquid extraction of a molten salt slipstream with liquid bismuth which contains electrochemically-generated metallic lithium (and/or metallic thorium). ORNL originally developed LBR/E to enhance the breeding performance of its two-salt MSBR because BR was the AEC's chief figure of merit. The rationale is that since 27-day half life  $^{233}\text{Pa}$  has a fairly high absorption cross section, if it were to be

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<sup>20</sup> The core-wall neutron flux of my 400 MW<sub>e</sub> example (Fig. 8) would be about  $4.8 \times 10^{21}/\text{cm}^2/\text{year}$ . Since good graphite is supposed to be able to withstand  $\sim 3 \times 10^{22}/\text{cm}^2$ , its replacement interval would be just over 6 years. Pyrolytic carbon-overcoated silicon carbide tubes would probably last longer.

<sup>21</sup> Cycle times can vary over a wide range depending upon how trade-offs are weighted; e.g., shorter blanket salt cycle times would generate less FP in the "wrong" place and slightly increase BR but require bigger process equipment.

<sup>22</sup> For Fig 8's example, a 2 month fuel salt clean up cycle corresponds to a flow rate of 5.6 liters/hr ("tiny").



quickly removed from the blanket salt and stored outside of the neutron flux, less of it would transmute before decaying to  $^{233}\text{U}$ .

## 4.2. Other MSBRs

In 1968 someone proposed that LBR/E *might* also be able to separate thorium and rare earth FP as well as Pa and thereby permit a “simple” MSBR because thorium could be added to the fuel salt (just one salt stream instead of two) without generating an impossibly high amount of radwaste<sup>23</sup>. Since “simple” sounded good to the AEC, ORNL spent the last four years of its active MSBR research era (1969 to 1973; e.g., ORNL 4541) trying to make that concept work. Unfortunately, achieving adequate separation proved to be “difficult” which means that implementing a one-salt MSBR capable of breeding its own fuel would also be “difficult”. Equally unfortunately, this approach seems to be the only one that DOE seems to be willing to remember (Fig. 9).

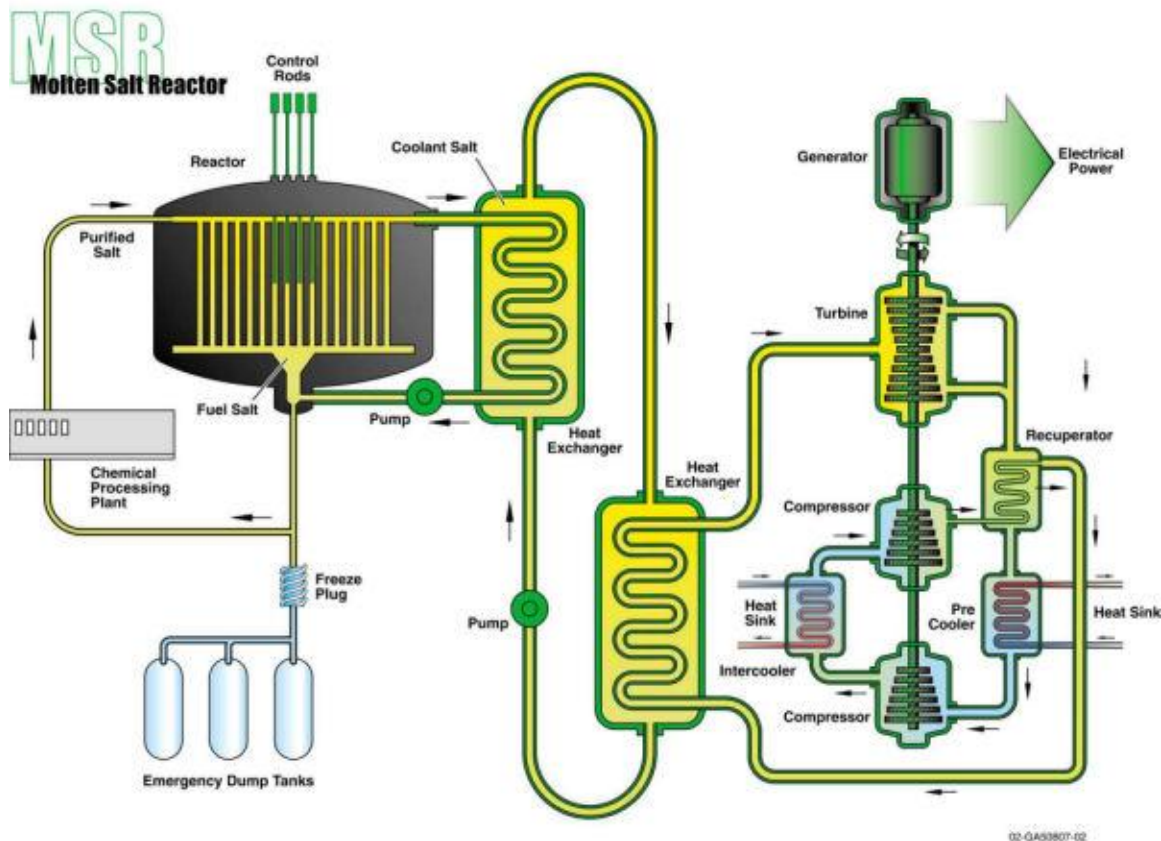


Figure 9: DOE's "MSR" Gen VI option (from INL website)

DOE's "MSR" is identical to the ones depicted in ORNL's one-salt MSBR era reports with the sole exception that a modern multi-reheat Brayton gas (He) Cycle turbine replaces the original steam turbine (an advantage). All one salt MSBRs have the following drawbacks:

<sup>23</sup>

If these separations don't work, most of the thorium will end up in the discard pile.

- Mixing thorium with the fuel salt tremendously complicates salt clean up (chemical problems are often glossed over by nuclear engineers).
- It raises proliferation issues because rapid (a few day cycle time) Pa removal/isolation is necessary to achieve breakeven fissile regeneration. Evil-doers *could* utilize on-site Pa isolation equipment to isolate  $^{233}\text{U}$ <sup>24</sup> uncontaminated with  $^{232}\text{U}$  - a good bomb-making material.
- Thorium creates a relatively “dirty” core salt that requires more fissile to overcome; i.e., one-salt reactors possess greater fissile requirements/MW<sub>e</sub>.
- Graphite moderation is both unnecessary and problematic. In a clean-core MSBR, neutrons travel far enough for the FLiBe to sufficiently moderate them. The tightly fitting bundle of graphite hexagonal fuel tubes evoked in most one-salt MSBR concepts would be prone to neutron irradiation damage and very difficult (expensive) to replace. Spent moderator graphite would also constitute radwaste - in the case of ORNL’s twenty foot high, 22 foot diameter 1 GW<sub>e</sub> one-salt concept, about 300 tonnes of it<sup>7</sup>

The MSR represents an unnecessarily problematic, risky, and expensive way to go about implementing a MSBR.

## 5 HOW MUCH MORE RESEARCH DO WE NEED?

The answer to this depends upon whether one’s career goal is to find something to “study” until retirement or build a genuinely sustainable reactor. To oldsters familiar with the rate at which things were accomplished by the folks who worked for both General Groves and Admiral Rickover, there is no good reason why the first example of the recommended tube-in-shell configured MSBR couldn’t be built within five years. The key technical issue is coming up with an affordable, readily maintained (replaced) “barrier” (core) tube - all graphite? C-C composite? C-SiC composite?...flanged? welded? This can’t be determined with “systems analysis” - large scale testing performed under realistic conditions must be performed. Regardless of the rationale currently proffered for NGNP, there is absolutely no need to assume that MSBR must operate at even higher temperatures - and therefore insist that all of ORNL’s material corrosion work be redone first. The theoretical thermodynamic efficiency advantage of operating at 900°C instead of 700°C isn’t worth the associated technical risk and inevitable delay.

## 6 PROSPECTS FOR “CHANGE”

The National Academy of Science’s recent review<sup>8</sup> of DOE’s nuclear reactor development programs includes the following statement:

*“DOE has selected the VHTR as a priority concept but has given some support to other (Gen IV) concepts EXCEPT the MSR where DOE has only funded the monitoring of international activities and university-based programs”.*

<sup>24</sup> Recent French reports indicate that the “fresh” fissile generated in a two salt MSBR would contain about 600 ppm  $^{232}\text{U}$  - enough to render bomb making with its fissile both suicidal and easily detectable.

This suggests that the likelihood of Weinberg & Goeller's rosy scenario being implemented with any sort of nuclear reactor is less now than it was back in 1974.

One reason for this is exemplified by the fact that the folks currently leading the charge for a "nuclear renaissance" here in the USA, INL's NE R&D managers, are cautioning their employees to not use the word "breeder" in their reports or even be "judgmental" in evaluating other alternative energy schemes (e.g., algae-based biofuels) investigated by other DOE-sponsored research teams. Similarly, our leaders' apparent confusion about what a future generation of nuclear reactors is supposed to accomplish<sup>25</sup> has spawned a host of new names & "missions" for hoary concepts. For instance DOE/INL's current front running Gen IV reactor candidate, the Very High Temperature Reactor (VHTR aka NGNP) is another remake of the almost four decade-old Ft. St. Vrain -type High Temperature Gas cooled Reactor (HTGR) currently being promoted as a uniquely efficient hydrogen producer – perhaps to complement Mr. Bush's brilliant "Freedom Car" initiative. DOE/INL's runner-up Gen IV concept, the "Sodium Fast Reactor" (SFR) is basically the same liquid metal cooled fast breeder reactor (LMFBR) that our grandparents were hearing about fifty years ago – the difference is that it is now being touted as a uniquely efficient way to burn the TRU (mostly plutonium) in the "spent" fuel rods which have been accumulating at reactor sites – not as a breeder.

Another thing rendering the prospects for substantive change unlikely is the fact that for several decades, DOE has recruited most of its top NE decision-makers from the US nuclear industry and the US Navy. Both of those institutions are bastions of conservatism and most of their top-level employees have a financial interest in growing the status quo, not "change". A final institutional issue is that DOE has also been encouraging its contractors to destroy ("decommission") most of its experimental facilities and down-size the "old timers" who know how to perform hands-on experimental work with "dangerous" stuff in them. Those laboratories/pilot plants have been replaced with tidy new office buildings staffed with desk-bound computer modelers (aka "systems analysts") with nuclear engineering degrees. Basically this situation means that any "old" idea which wasn't exhaustively tested/documented back when it was actually possible to do so, is apt to be deemed too risky (too hard to model) to be seriously considered today<sup>26</sup>.

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<sup>25</sup> Be so "proliferation resistant" that we could confidently let terrorists run them? Be so "safe" that electrical utility CEO's could staff-up with technically illiterate, minimum wage, workers? Burn the TRU in spent LWR fuel so that our decision makers won't have to agonize about Yucca Mountain for another three decades? Keep the "nuclear establishment" well fed? Produce cheap sustainable nuclear power? (BINGO!) ....

<sup>26</sup> Hyperion's "nuclear battery" currently suffers from this institutional pathology. It is based upon an idea which makes good technical sense and was therefore granted a US patent over twenty years ago. However, in spite of the fact that its inventor worked at one of DOE's premier nuclear (bomb) research institutes (LANL), it was never reduced to practice which means that it is now almost impossible to convince our nuclear "watch dogs" (esp. the NRC) that it's "safe" enough to license. Basically this just means that another invented-in-America technology will probably end up being developed elsewhere, therefore chiefly benefiting that country, not ours (the transistor is the classic example – Sony's transistor radio gave Japan's electronic industry a huge head start that the USA never quite managed to catch up to).

It's not difficult to understand why the scientists and engineers employed by our national laboratories behave the way they do. It quickly becomes obvious to anyone coming to work at them that openly challenging DOE's assumptions/dictates about how its "missions" are to be addressed – especially in a public forum - guarantees that the remainder of your career there will be "solitary, poor, nasty, brutish, and short". Young professional people who still have to pay for their home, car(s), and children's educations/periodontal work, can't afford to be as forthright as us old-timers can. Weinberg's fate back in 1973 (downsized for committing thought crime) is unusual only in that he had lots of other good job opportunities.

The real issues we face include: a) total lack of support by a vendor-dominated nuclear establishment that equates nuclear power with uranium; b) a general unawareness of either how critical this country's energy problem has become or of how unrealistic most of the "alternatives" being offered really are; c), a cowed and therefore militantly incurious Federal R&D workforce; and, d) a US technical infrastructure which has been seriously compromised by several decades of outsourcing. If positive change is to happen, it'll probably have to come from a younger generation - maybe from the folks attending this conference.

## **CONCLUSIONS**

Our country's refusal to implement the sort of bullet-proof repository dictated by the TRU content of spent LWR fuel means that we must either adopt a nuclear fuel cycle that doesn't generate TRU and then build lots of reactors utilizing it or accept the fact that we're consigning our grandchildren to live in a country which is much poorer than the one we were born to. It is unrealistic to believe that China's leadership will deliberately choose to handicap their country's chances for a prosperous future for the sake of political correctness. The USA must take the lead in making Weinberg's dream a reality – it's the key to our future.

## **ACKNOWLEDGEMENT**

We would like to thank the folks at GOOGLE for making it possible to obtain almost any sort of technical information one is willing to dig for. I (DDS) caught the "thorium bug" at Bruce Høglund's website, <http://home.earthlink.net/~bhoglund/> -and then discovered Kirk's Sorensen's monumental "energyfromthorium" web/blog site with its marvelous essays, discussion forum, and "document repository" containing all of ORNL's molten salt related research reports, publication, books, etc., plus just about everything else that's ever been written about molten salt reactors. Kirk's recent GOOGLE Tech Talk is an excellent introduction to the field. Dr. David LeBlanc's publications, numerous "energyfromthorium" discussion forum postings, Google Tech Talk, and personal communications have been especially helpful. Finally, I'd like to thank the WIKIPEDIA "techies" who have rendered ignorance about most things inexcusable.

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